Statistical modelling of air pollution and the challenges of communication

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CASI2018

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Context

- Winter pollution - particulate matter $\leq$ 10 microns (PM_{10})
- Predominantly home heating (e.g. open fires, inefficient log burners)
- PM_{10} concentrations well above WHO guidelines (e.g. daily average of 50 $\mu g/m^3$)

- Strongly linked to various medical conditions, incl. respiratory and cardiac problems
- Linked to increased mortality
- Social costs estimated at over NZ$4 billion per year (€2.5 billion)

National Environmental Standards

- Govt set National Environmental Standards for Air Quality:
  - **Daily average** PM_{10} concentrations (midnight to midnight)
  - maximum number of exceedances of target level $50\mu g/m^3$
    - no more than 1 exceedance by 2020
- Regional councils responsible for implementation
- Various central, regional and local government initiatives to achieve these targets

- Winter PM_{10} concentrations are mainly driven by:
  - emissions - meteorology and number of burners used
  - meteorology directly

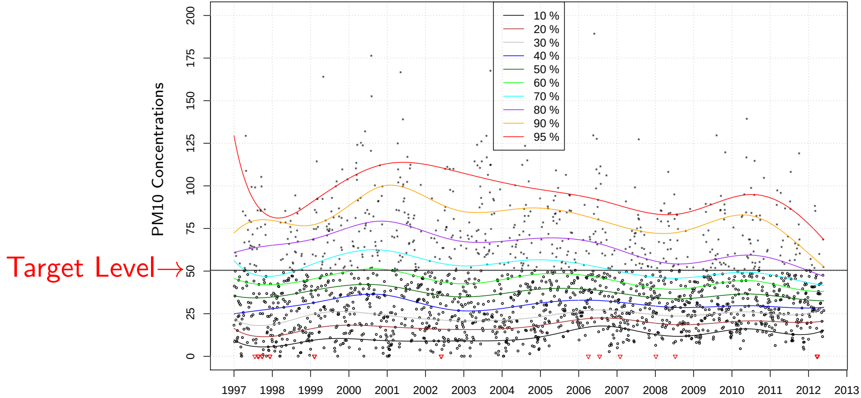
Key Questions of Interest

1. What is the current situation and have the govt initiatives been effective?
2. What % reduction in the emissions (e.g. inefficient log-burners) is needed to achieve the targets?

In more statistical terminology:

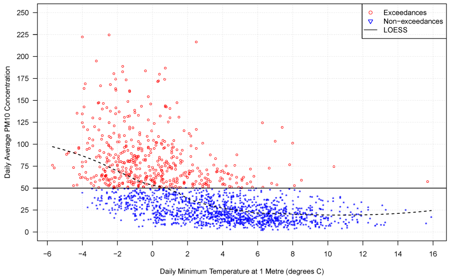
1. Statistical model of the meteorological impacts on the concentrations along with historical (slowly varying) trend to capture changes in extent of burner usage.
   - Is their evidence for a decreasing trend since 2003?
2. Estimate % reduction in the concentrations needed to reach future targets with a certain probability, taking into account random meteorological variation and model uncertainty

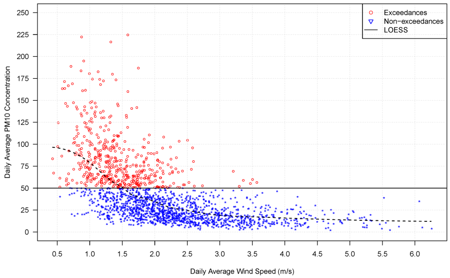
Daily Average Winter PM_{10} Concentrations



- Typical exceedance night: cold, calm and no rain (possibly with temperature inversion)
- Only winter data (May-August) as few exceedances in summer and these are caused by different factors
- Notice spurious lack of low concentrations since 2005

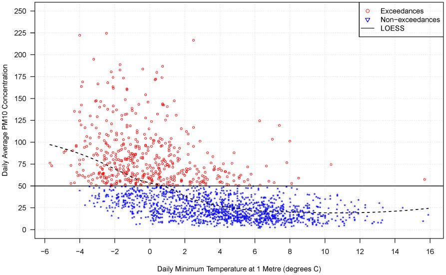
Meteorological Impacts

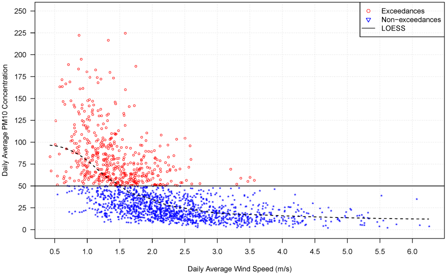




- Key predictors: temperature and wind speed
- Negative exponential form so model mean on log-link scale
- Secondary predictors: rainfall, soil temperature, wind direction, relative humidity and cloud cover/height

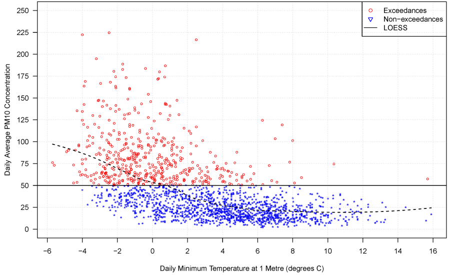
Meteorological Impacts

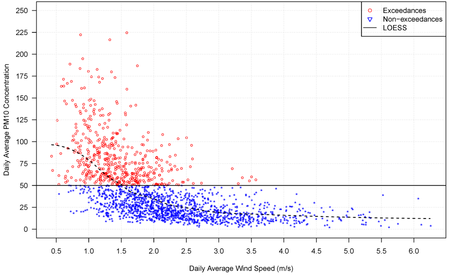




- Hourly meteorological data
- Aggregated to daily statistics: mean, **minimum**, **maximum** and **standard deviation**

Meteorological Impacts





- Extra complication:
  - Legal definition 24 hour is midnight to midnight
  - Physical reality ∼3PM to ∼3PM
- Need previous evening's meteorology

GAMM for Daily PM_{10} Concentrations

- Generalized additive mixed model on log-link scale $g(\mu) = \log(\mu) = \eta$

$$\eta = \boldsymbol{X}\boldsymbol{\beta} + f_1(t) + f_2(t) + \ldots + f_k(t)$$

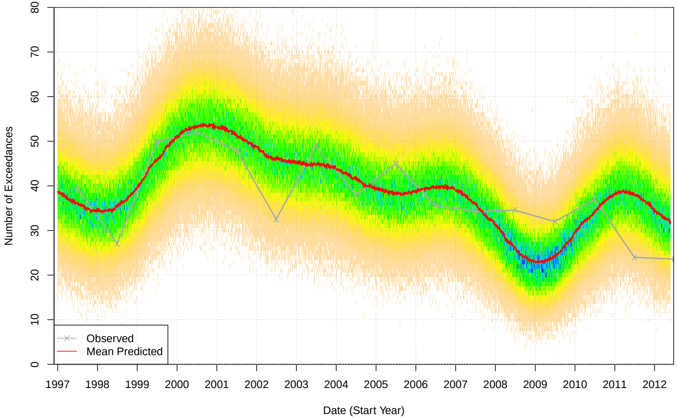
- Meteorological fixed effects as linear predictors (following some careful model selection)
- Slowly varying function of time t:
  - thin plate regression splines ($\sim$ 7-8 d.f.)
- Distribution family:
  - Normal(μ, σ^2) - constant variance? Negative concentrations?
  - Gamma(α, β) - variance $\propto$ mean and positive concentrations (physically sensible but not robust to data issues)
- AR(1) to capture residual autocorrelation

Simulations to Visualise Model Fit

- Take estimated smooth trend on a particular day and fix it for whole winter period
- Simulate potential winter weather patterns using historical meteorological data vectors:
  - Randomized block length (stationary) bootstrap
  - Average block length of 5 days
  - Gives simulated weather for all 123 days of winter
  - Repeat 10,000 times
- Apply GAMM to get predicted concentrations $\hat{\mu}_{sim} = \exp(\hat{\eta})$
- Simulate "observable values" of PM_{10} concentrations from GAMM distribution (normal, gamma, ...)
- For each "simulated winter" extract relevant statistics:
  - number of exceedances
  - second largest PM_{10} concentration
  - fourth largest PM_{10} concentration

Results for Number of Exceedances

- Simulated statistics were much easier to explain to scientists and policymakers:



- Satisfactory model diagnostics and estimated trend is consistent with observed behaviour
- Large deviation in 2012 due to partially observed year

Simulate From Model For Forecasting

- Back to second question...
  - Estimate % reduction in the concentrations needed to reach future targets with a prescribed probability, taking into account random meteorological variation and model uncertainty

- Use simulations to estimate total % reduction required
- Prescribed probabilities of 50% and 95%
- Use estimated trend in current year as baseline level
- Inverse problem to find % reduction needed to get 50% of "simulated winters" to have at most 1 exceedance by 2020

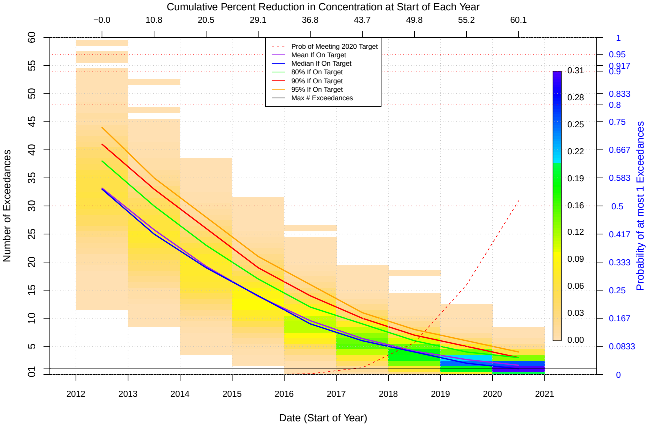
Simulate From Model For Path to Compliance!

- Using the total % reduction needed by 2020, consider potential "**paths to compliance**"
  (sorry for the management speak!)
- Apply linear trend on log-scale, to give **constant % reduction each year**
- Use simulated distribution of:
  - number of exceedances
  - second largest concentrations

  to get tolerance limits per year when "city is on target"
- i.e. to allow for fact that city could be on target, but may have a particularly cold winter by chance

Path to Compliance With 50% Probability

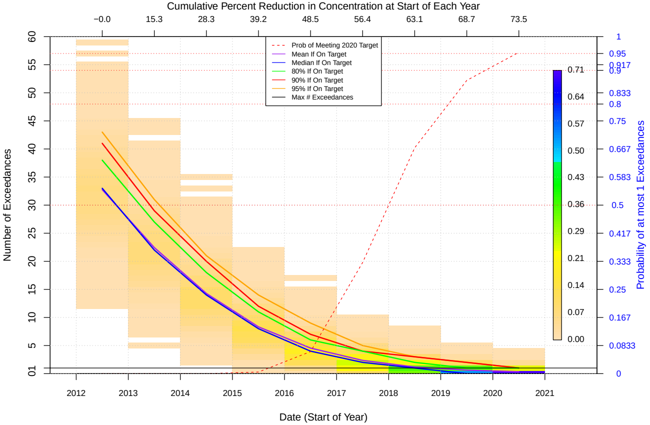
- Total estimated reduction of 60.1% of PM_{10} concentrations
- Annualised value of 10.8%



- Aim at (median, blue line) at 1 exceedance by 2020, as expected
- Green/red/orange lines are tolerable limits on number of exceedances if on target, to allow for worst 20%, 10% or 5%

Path to Compliance With 95% Probability

- Total estimated reduction of 73.5% of PM_{10} concentrations
- Annualised value of 15.3%



- Aim at less than 1 exceedance by 2020!
- Second largest PM_{10} concentration aim of $42\mu g/m^3$ for 95% chance of meeting 2020 target

Summary for Complying by 2020

		2013	2014	2015	2016	2017	2018	2019	2020
50% Chance of Meeting 2020 Target									
Annual % Reduction		**10.8**							
Cumulative % Reduction		10.8	20.5	29.1	36.8	43.7	49.8	55.2	**60.1**
Target Values	# Exceed.	26	19	14	9	6	4	2	1
	Second Larg.	88	80	73	67	62	58	54	50.5
90% Up Limit	# Exceed.	33	25	19	14	10	7	5	3
	Second Larg.	99	90	83	76	70	66	61	58
95% Chance of Meeting 2020 Target									
Annual % Reduction		**15.3**							
Cumulative % Reduction		15.3	28.3	39.2	48.5	56.4	63.1	66.7	**73.5**
Target Values	# Exceed.	23	14	8	4	2	1	0	0
	Second Larg.	84	74	65	59	53	49	45	42
90% Up Limit	# Exceed.	29	20	13	8	4	3	2	1
	Second Larg.	95	84	74	66	60	55	52	48

Summary and Further Work

- Interesting application bringing together statistical modelling and simulation
- Provides scientific justification to inform government policy

- Earthquakes changed priorities
- From air pollution viewpoint, major improvement to housing/heating in Christchurch due to rebuild

- Further work to do:
  - uncertainty due to "estimating current state"
  - robustness to data issues
  - alternative modelling approaches (exceedances are extremes)
  - multi-site extensions